BRIEF OVERVIEW ON NOVEL NUCLEAR ENERGY GENERATION TECHNOLOGIES AND INSTRUMENTS

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Nuclear reactor technology has been under continuous development since the first commercial exploitation of civil nuclear power in the 1950s. This technology is presented at different stages, or "generation" of nuclear reactor development, each representing a significant technical step advancement compared with the previous generation. Nuclear power is the principal carbon-free source of electricity, and therefore plays a key role in limiting greenhouse gas emissions.
Improving scientific and technical knowledge and competences in the areas of safety, sustainability, security, reliability and cost effectiveness of nuclear energy and other applications of nuclear technology are one of the main tasks of world science and technology community.
The paper represents the analyze of existing level of nuclear energy systems development
The primary task in this research area is to coordinate the development of concepts and processes that can address the key outstanding issues in elaboration of novel effective technologies and constructions for nuclear energy preparation.
It is shown that performed theoretical, physica-technical and technological research works clearly indicate the prospects of using new materials, devices and designing schemes for creation of highly effective energy generating and control and safety systems for different nuclear reactors.
Particular attention was paid to the development of new and upgrading of existing technologies for designing and preparing the optimizing nuclear technology methods and tools for obtaining desirable operational parameters of nuclear instruments such as rods of control and safety systems of nuclear reactors.

Key words: Nuclear reactor technology, nuclear energy systems, energy generation technology, proton, safety research.

Introduction

Current forecasts indicate that the primary energy consumption worldwide by 2050 will probably will doubled in comparison with the year 2000. Energy security is becoming a major global concern. Fossil fuel reserves, particularly for crude oil, are confined to a few areas of the world.

Political, economical, and ecological factors often force volatile and high fuel prices [1]. Simultaneously, to combat climate change, a global environmental policy which includes a major reduction in greenhouse gas emissions is required.

One of the statements presented in Brundtland Report [2] is underlining: Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Following this, sustainable nuclear would ensure security of supply of electricity at predictable prices over reasonable periods (Fig.1.).

Now it is obvious that nuclear energy both nuclear fission and fusion is a key element for future environment friendly energy generation technologies creation. Nuclear fusion – a very prospective energy generation technology requires the wide research works until it will be consider for transferring to energy production industrial facilities (Fig.2).

Nuclear fission energy nowadays can deliver safe, sustainable, competitive and practically carbon-free energy to citizens and industry. It is based on short-, medium- and long-term development of nuclear fission energy technologies, with the aim of achieving a sustainable production of nuclear energy, a significant progress in economic performance, and a continuous improvement of safety levels as well as resistance to proliferation.

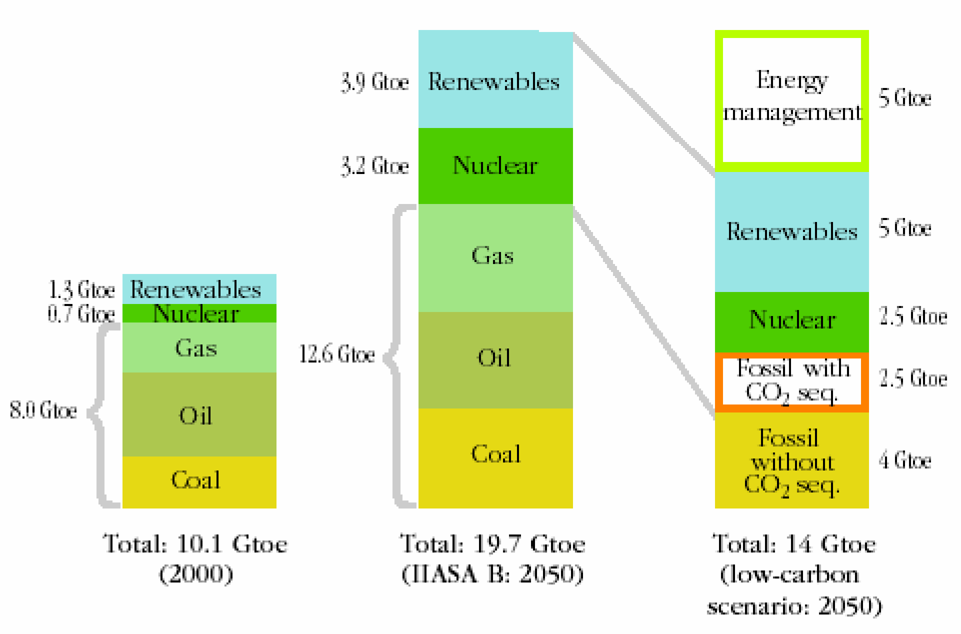

Fig. 1. Possible role of nuclear energy in different scenarios for 2050: example of a 14-Gtoe/year scenario where nuclear energy would represent 2.5 Gtoe (corresponding to an installed capacity of 1 300 GWe)

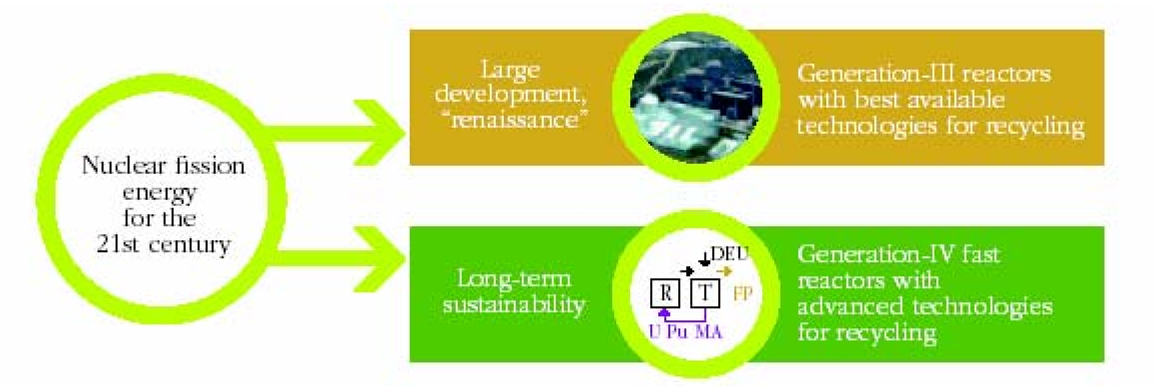

Fig. 2. The vision for future nuclear energy Renaissance and long-term sustainability of nuclear energy: R – recycling; T-transmutation; U-uranium; Pu-plutonium; MA-minor actinides; DEU- depleted uranium; FP- fission products

Following challenges are taking into consideration and performance: Perspective of an important development of nuclear energy in the world relying on III generation of light water reactors; The development of generation IV fast neutron reactors with closed fuel cycle; Elaboration of combined Nuclear – Hydrogen energy generation technologies; elaboration of effective and workable nuclear fusion technologies and reliable ideas of proton based nuclear technologies.

Nuclear energy systems: Inherent problems and prospective

The main problems of nuclear energy generation technologies and facilities are:

Safety – Necessity of confinement of nuclear radiation substances for prevention from going in to the public's irradiated;

Waste – Radioactive waste has a very long half-life which compared with whole life history on the Earth. Radioactive wastes will be generated during nuclear energy preparation cycle, and it will be existed over a long period after withdrawal from nuclear energy. The radioactive wastes increase in proportion to the cumulative operation time of nuclear reactor. Therefore this is the difficult problem always accompanying nuclear energy usage;

Nuclear Proliferation – The problem of civil using of nuclear energy is its similarity with materials and technologies for nuclear weapons preparation. Proliferation problem will not disappear when nuclear reactor stops the operation. It should be controlled to avoid production of nuclear weapons on the basis of developed skills, technologies and materials.

The expansion of nuclear power must maintain the highest standards of nuclear safety, security,

and nonproliferation.

There are some key factors to successful construction and operation of nuclear power facilities:

Economic competitiveness and financing; Public acceptance; Nuclear fuel (Uranium, etc.) resources; Safety and reliability; Fuel and waste management; Human and industrial resources;

Proliferation risk and security; Infrastructures, especially in new nuclear club member countries. [3].

In the last years also were elaborated the 19 issues for consideration in each phase of nuclear power development: National position; Legal framework; Regulatory framework; Radiation protection; Financing; Human resource development; Safeguards; Security and physical protection; Emergency planning; Nuclear fuel cycle; Nuclear waste; Environmental protection;

Nuclear safety; Sites and supporting facilities; Stakeholder involvement; Electrical grid Management; Industrial involvement; Procurement (Fig.3)

The very important issue for nuclear energy farther development is Social Acceptance which is based on four principle conditions that it takes for co-evolution of science technology and society. a) Science and technology have formed a healthy evolutionary system; b) The values of bodies that play a role in science and technology are reflected in the values of modern society; c) The values created by science and technology are appropriately examined by society, which recognizes them properly; d) Society has a certain amount of confidence in science and technology, and groups involved with it (Fig.4 and Fig.5).

Nuclear energy generation systems development and novel nuclear reactors.

During last two decades it was established the concept of nuclear power development in the 21st century, which includes the following stages:

- Near-term (10-20 years):
  Evolutionary development of reactor and fuel cycle technologies (light water nuclear reactor - LWR, aqueous reprocessing); development and trial operation of advanced and innovative reactor and fuel cycle technologies (fast reactors, small reactors, dry reprocessing).
- Middle-term (30-40 years):
  Fast growth of nuclear power; demonstration and introduction of innovative technologies; high-temperature reactors; small reactor facilities; hydrogen production and water desalination.
- Long-term (50-100 years):
  Large-scale deployment of the innovative technologies of naturally safe fast reactors and fuel cycle; fuel breeding; closed U-Pu and Th-U cycles; use of valuable isotopes and burning of hazardous nuclides; long-term geological isolation of radioactive waste [4].

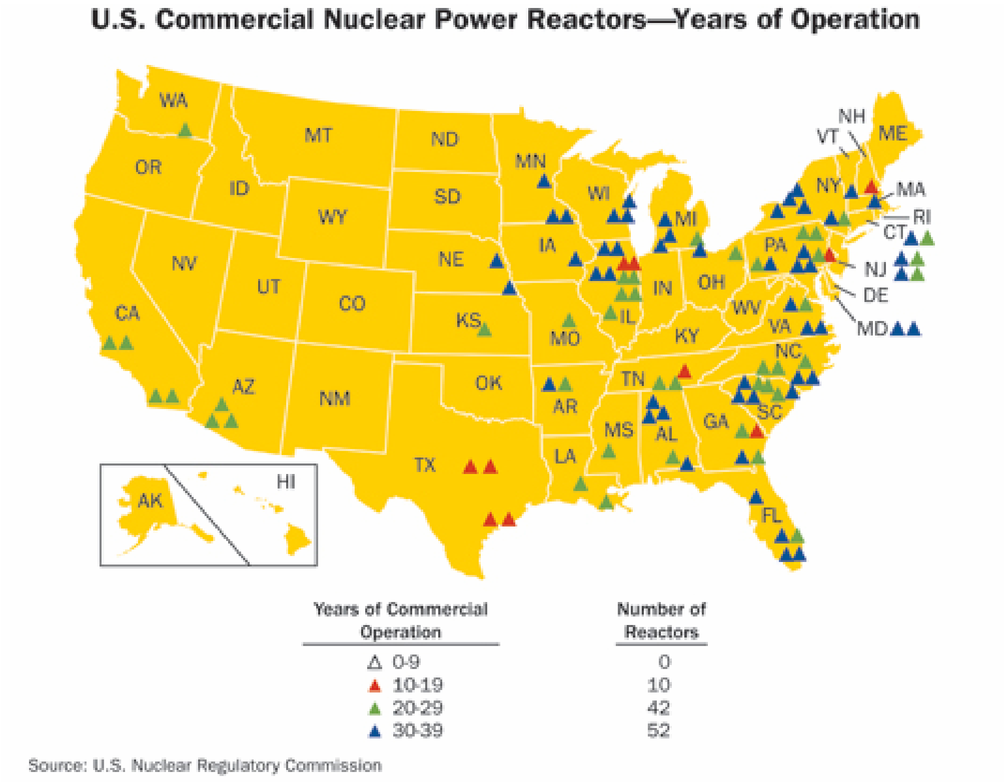

Fig. 3. 104 U.S. nuclear power plants

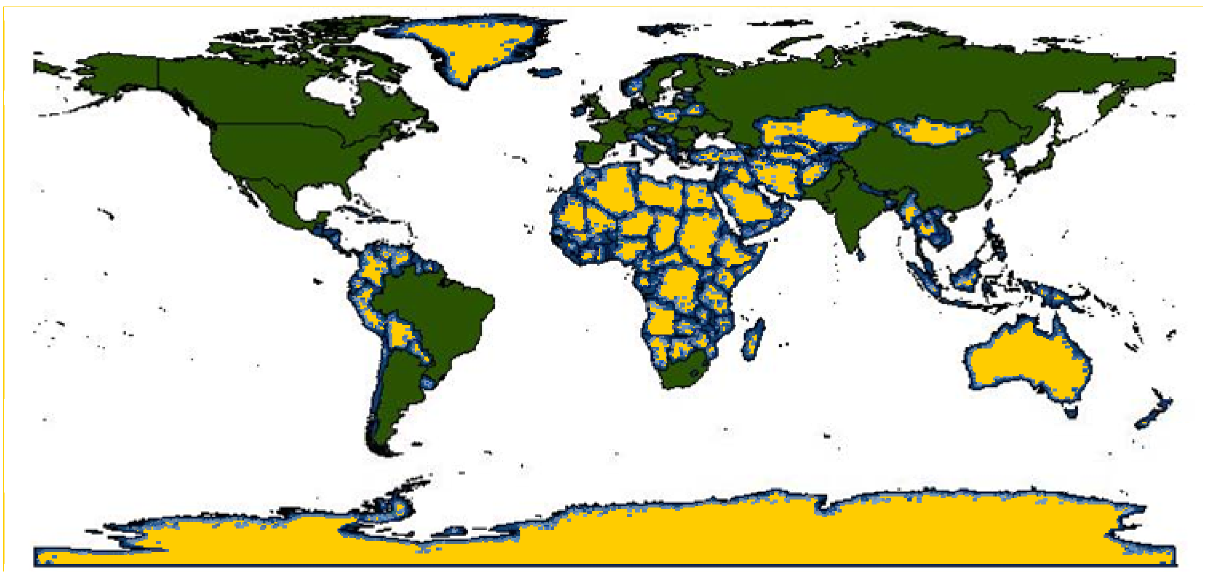

Fig.4. Nuclear power today
✸ States with nuclear energy programs

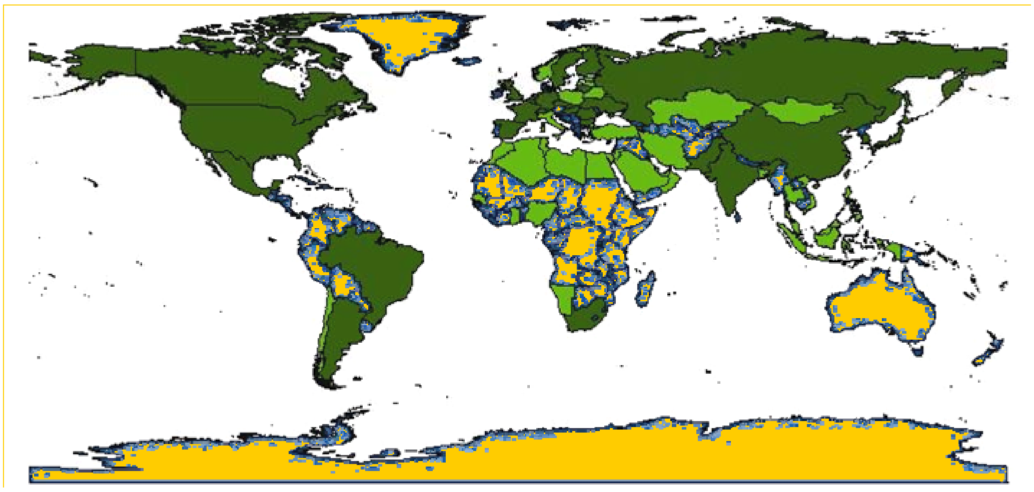

Fig.5. Nuclear power tomorrow
✸ States with nuclear energy programs
✸ States considering nuclear energy programs

For nuclear power systems today we are considering the three fuel cycle alternatives:

- Traditional thermal reactors with an "open" fuel cycle in which fuel is removed from reactors and sent to a disposal site;
- Thermal reactors with a "closed" fuel cycle (France, Russia, Japan) in which plutonium is extracted from the spent fuel and then re-used to fabricate once-through mixed uranium - plutonium oxide (MOX) fuel;
- A two-component system incorporating thermal reactors with an "open" fuel cycle and a properly balanced number of fast reactors burning actinides separated from the spent fuel of thermal reactors. The fast reactors, fuel reprocessing and fabrication facilities should be placed together in safe nuclear "parks".

Following all above mentioned last decades became possible to introduce the new generations of nuclear reactors and relevant nuclear generation facilities: Third generation of nuclear plants

meets modern safety and environmental standards and requirements and resolve the current energy problems, but still far from being perfect as regards economics, fuel supply and proliferation resistance; Fourth generation of nuclear plants - new reactors and fuel cycle technologies ensure gradual transfer to safe and competitive heat and electricity generation with unlimited fuel resources relying on inherent production of fissile isotopes.

For current light water nuclear reactors, the spent fuel can be recycled at least once into mixed oxide fuel. This one must be stored, in order to recover the plutonium to be used for a future generation of fast reactors-breeders which can effectively burn this plutonium in a multirecycling uranium-plutonium strategy. Basically, 50 years of operation of one LWR will produce the stock of plutonium needed to start a fast reactor – which could thus form a sustainable source of energy for thousands of years through the use of depleted uranium [5]. The next stage is related to the recycling of minor actinides to reduce the thermal load, the volume and the needed isolation time of the remaining waste requiring geological disposal. Recent R&D results have shown that minor actinides can be separated from spent fuel, thus opening the way for their burning in a fast-neutron system, thereby using their energetic potential, as well as eliminating them as long-lived radioactive material.

Beyond the use of nuclear power for electricity generation, new applications are being developed, based on generation-III or -IV reactor features, in particular through the coupling of (very)-high-temperature reactors with chemical processing plants (BN 350 nuclear reactor based Mangishlack power plant, Kazakhstan). An international conference [6] organized some years ago by the IAEA (International Atomic Energy Agency), in cooperation with the OECD/NEA (Nuclear Energy Agency) and the International Desalination Association, has provided a broad survey of non-electric applications of nuclear energy. These include: processes for producing alternative energy carriers replacing for example the use of oil for transport, including hydrogen and bio-fuel production; processes that require heat and/or electricity, such as desalination.

Generation-III reactors, such as the EPR (European Pressurized-water Reactor), are evolutionary reactors derived from the experience of operating LWRs and developed to optimize their safety and economic performance. They are currently being deployed in Finland and in France, which both chose an EPR design, with commercial operation planned to start around 2010 and 2012 respectively. These new reactors are designed to be operated for 60 years. In the longer term, generation-IV systems will take over once they have reached technical maturity and met sustainable development criteria, particularly those pertaining to waste management and preservation of energy resources.

In European Union countries, a total of 152 Generation-II light-water reactors are in operation. The average age of these power plants is approaching 25 years for a typical initial design life of 30-40 years.

To meet the growing concerns about security of energy supply and CO2-emission reductions before LWRs of generation III can be built and operated, a first priority is given to lifetime extension of generation-II LWRs. While maintaining a high degree of operational safety, the already well-proven economic competitiveness of nuclear energy can be further enhanced by research focused on improved availability, fuel performance and safety.

With the European Pressurized-water Reactor (EPR) in Olkiluoto, Finland was the first country in Europe to launch the construction of a new nuclear power plant (NPP) for more than a decade. It was followed by France in 2006, with the decision to build another EPR plant in Flamanville.

Nuclear market renaissance with the construction of a large number of NPPs will necessarily rely on generation-III LWRs, which offer enhanced safety and reliability and the best available technologies for a responsible management of spent nuclear fuel.

Spent fuel treatment and recycling of uranium and plutonium are already an industrial reality in some countries, such as France, Japan and Russia [7].

The future of nuclear power is trusted now to fast reactors and closed fuel cycle. This implies reprocessing of the spent fuel of nuclear plants and re-use of plutonium produced in power reactors, which may raise the energy potential of nuclear fuel resources ~ 100 times.

Owing to their unique neutronics, fast reactors are capable of burning the most long-lived nuclear wastes.

Fast reactors have been chosen as the baseline in the Strategy of Nuclear Power Development in the First Half of the 21st Century, and as a promising energy technology in the international programme Generation IV [8].

Spent fuel treatment and multi-recycling is the basis on which future generation-IV reactors will achieve sustainability. Fast neutron reactors with a closed fuel cycle allow: significantly improved usage of natural resources, minimization of volume and heat load of high-level waste.

This option has been selected by several countries, such as Japan (with JSFR, Japan Sodium-cooled Fast Reactor), Russia (with the BN 600 in operation and the BN 800 and BREST 300 reactors), India (with the PBFR prototype), China (with CEFR – China Experimental Fast Reactor) and the United States (with the advanced recycling reactor project). This option was also selected in Europe (with Phénix, PFR, KNKII, and Superphénix). In 2006, France launched a project to construct a sodium-cooled fast reactor (SFR) prototype by 2020, open to industrial and international partnerships. This could be considered as the first step towards a renewed European initiative. Among the fast reactor systems, the sodium-cooled fast reactor currently has the most comprehensive technological basis, thanks to the experience gained internationally from operating experimental, prototype and commercialized reactors such as the Phénix plant in France, PFR in the UK, and MONJU in Japan (Fig.6).

Fig. 6. Phénix sodium-cooled fast-neutron reactor in Marcoule (France)

The technological knowledge gained from these reactors includes key elements of the overall reactor design, fuel types, safety, and fuel recycling. Innovations are sought for a generation-IV sodium-cooled fast reactor in order to reduce costs and to further improve safety. They involve design simplification, improvement of in-service inspection and repair, fuel handling, high-performance materials, and practical exclusion of high-energy release in case of a hypothetical severe accident [9].

Given the maturity of sodium-cooled fast reactors, the next facility to be built in Europe will be a prototype reactor with a power-conversion system of 250 to 600 MW to demonstrate innovations with respect to existing SFRs and to pave the way for a first-of-a-kind generation-IV commercial reactor.

To face the major worldwide challenges described above, generation-IV fast reactors have to offer a choice of technologies so as to limit the overall technological risk and be able to satisfy various markets and degrees of public acceptance. While the SFR remains the reference technology, two alternative technologies for fast reactors, namely the gas-cooled fast reactor (GFR) and the lead-cooled fast reactor (LFR) are also elaborating. After selection of an alternative technology, an experimental reactor in the range of 50-100 MW will be needed to gain experience feedback by 2020 on this innovative technology.

Among the attractive features of the GFR, which is a high temperature reactor, the chemically inert and optically transparent coolant (helium) should be mentioned as well as the potential for producing hydrogen, synthetic hydrocarbon fuels and process heat. The most important challenges for this type of reactor are the development of materials resistant to the combined effects of high temperature and high neutron flux (refractory and dense fuel, thermal barrier) and the safety systems.

The LFR is identified as another potentially promising alternative fast-reactor type. Russia has gathered experience in building and operating small lead-alloy-cooled reactors in the 100 MWth range for naval propulsion. The pure lead-cooled LFR system offers the same advantages as the lead-alloy cooled reactors of operating primary systems at atmospheric pressure. As a power reactor, it also offers the potential of being competitive with present-generation LWRs in electricity generation, provided that the designers succeed in simplifying the primary system and eliminating the intermediate cooling system. Current R&D addresses some critical issues associated with using lead as a coolant for reactors in the power range of 1 GWe, such as weight and corrosion. In-service inspection, maintenance and repair remain also a common challenge for both liquid-metal coolants, sodium and lead.

In association with the development of a robust fast-reactor system, a flexible separation and treatment strategy needs to be assessed, aiming towards a closed fuel cycle which better uses the fertile resources by a multi-recycling of uranium and plutonium. This strategy includes the development of actinide chemistry, separation technology and minor actinide bearing fuels with reactor irradiation of such fuel. Such a coherent long-term strategy would allow the transition from the currently practiced mono-recycling of plutonium in light-water reactors (LWRs) to multi-recycling in generation-IV reactors.

Beyond this goal, recycling is also the cornerstone of a strategy for partitioning and transmutation of minor actinides, which would substantially reduce the radioactivity and heat load of the remaining high-level waste. As a result, the isolation time and repository space required in deep geological disposal would also be reduced.

For the incineration of minor actinides, the opportunities offered by accelerator-driven systems (ADS) will be compared to those of fast-neutron critical reactors on a technological and economic basis.

The design of nuclear systems relies on the “defence in depth” principle. It consists in the prevention of accidents and the mitigation of their consequences, and the protection of workers and populations against radiological hazards through the use of multiple barriers and safety systems. For the more recent reactor systems such as generation-III reactors, even extremely improbable accidents are taken into account. For example, the European Pressurized-water Reactor (EPR) was designed so that in the very unlikely event of a severe accident, radiological consequences would necessitate only very limited protective countermeasures in a relatively small area and for a limited time for the surrounding population.

The safety analysis of nuclear systems relies on a thorough understanding of the behaviour of the system in normal and accidental conditions, and increasingly on the use of advanced numerical simulation software and its validation through experimental programmes. For future reactors design, simplified tools can be developed and applied at first to carry out preliminary analyses of concepts and safety options. Once the design is known, more advanced safety evaluation software tools can be developed and applied. In order to contribute to the harmonization of safety practices in Europe and to better compare the safety aspects of the different reactor systems, the development of common tools and methodologies is favoured.

Nuclear reactors innovative developments.

During last decades the nuclear reactors of different novel design were development [10, 11]. And among them it is necessary to underline:

- Simplified vessel-type boiling reactors with natural circulation of coolant;
- Advanced pressure-tube reactors with inherent safety features;
- Pressure-tube reactors with supercritical coolant parameters;
- Transportable nuclear power plants for heat and electricity supply in the far-away and difficult-of-access regions;
- Sodium – cooled loop-type fast reactor;
- Naturally safe fast reactors with heavy liquid metal coolant;
- Small-power reactors.

The novel nuclear reactors have their own advantages which meet the relevant requirements of sustainability and safety (Fig.7). For instant in the pressure-tube power reactors refueling can be done by a refueling machine both off-load and on-load, without power reduction.

The equivalent dose rate in the reactor hall will not exceed 29 μSv/h (2.9 mrem/h) during on-load operation, owing to which this area may be attended by personnel.

Pressure-Tube plant is a single reactor-turbine unit (monoblock). Each circulation loop of the reactor circuit has its own feed water control valve. The configuration suggested by the designers allows limiting circulation pipeline diameters to 300 mm at a maximum.

The circulation circuit of 800 MW plant (-1000 MW) does not have check, isolation and fast-acting valves, which simplifies the plant operation and raises its safety and reliability.

The plant has natural circulation of coolant (Fig 8).

The nuclear reactor for small power plant includes: Three interconnected hydraulic circuits, the last of which houses all heating loads (turbo generator set, district heating or process steam boilers).

All primary circuit components (the core, intermediate heat exchangers, pressurizer, reactivity control and shutdown rods) integrated in one vessel. No non-isolated primary pipelines; ionizing sources and potentially dangerous working fluid, i.e. primary coolant, confined within a very limited space (compact arrangement). The core cooled due to the natural convection of the primary coolant.

There aren’t active elements with continuously moving mechanical parts, only passive safety systems. Independent heat removal system operates all the time to remove the decay heat and cool the reactor (Fig. 9).

The most attractive features of it are:

- Load-following operation irrespective of external conditions, such as short-circuits in a transmission line, complete disconnection of heat and electricity consumers;
- No refueling during 25 years of the plant service life;
- No need for spent fuel storage facility;
- Air cooling of safety systems and turbine condensers.

On the end of its design service life, the reactor facility is completely removed from the site and delivered to a dedicated plant to be dismantled and disposed of.

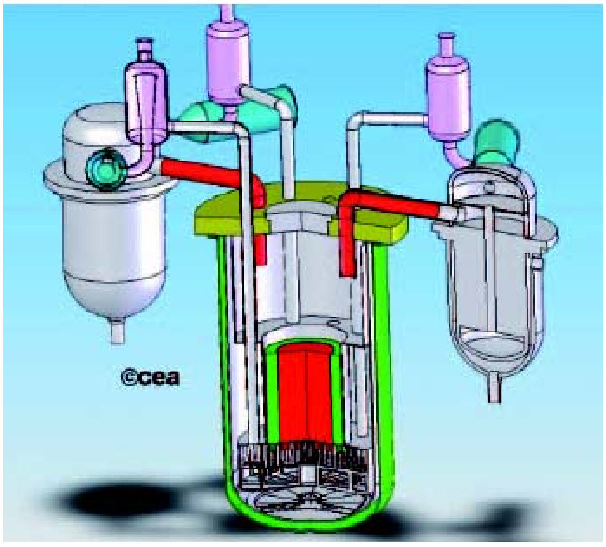

Fig. 7. Design of an innovative loop-type SFP

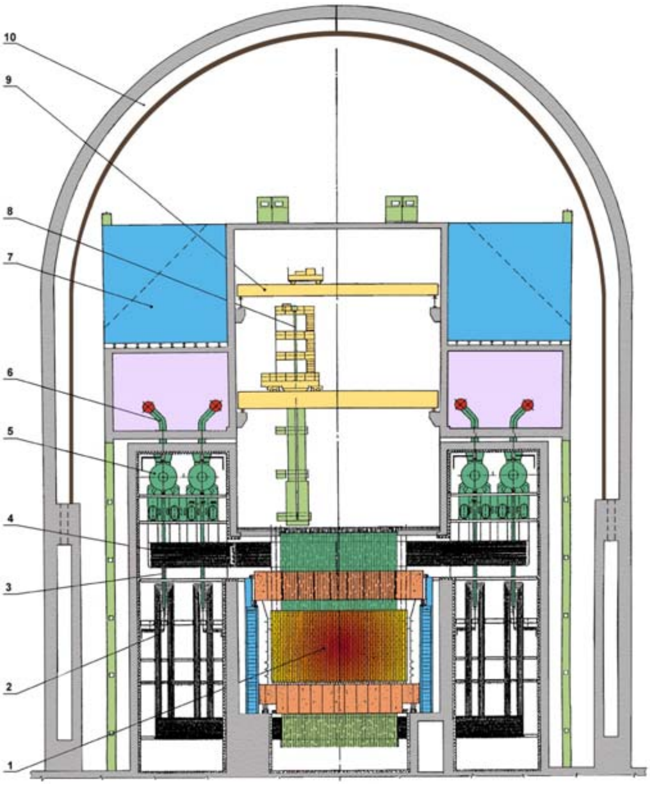

Fig. 8. Pressure-Tube power reactor
1 – reactor core; 2 – water lines; 3 – downcomer; 4 – steam-water lines; 5 – steam separator;
6 – steam line; 7 – passive cooling system tank; 8 – refuelling machine;
9 – bridge crane; 10 – containment

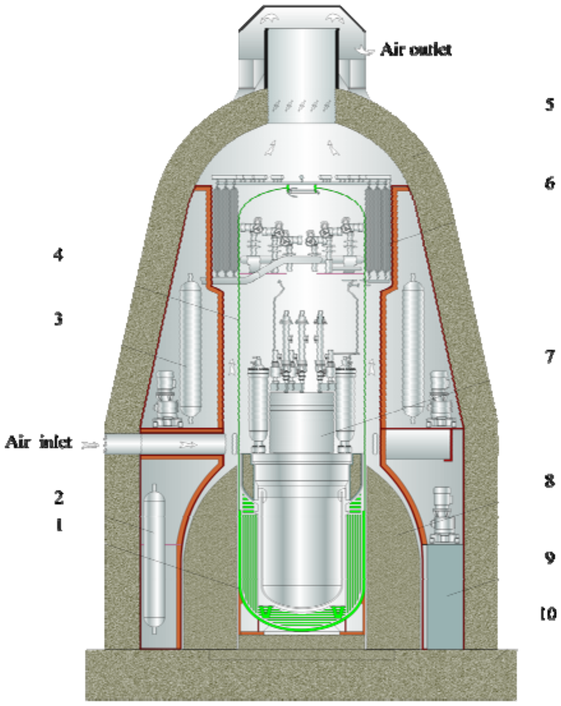

Fig 9. Small power plant
1 – iron-water shielding tank; 2 – gaseous waste storage tanks; 3 – liquid poison supply system; 4 – containment; 5 – shock-proof shell; 6 – heat exchanger of the cooling system; 7 – steam generating unit; 8 – biological shielding blocks; 9 – liquid and solid radwaste storage facility; 10 – foundation

The very important safety features has a new designed nuclear reactor -1200 MWt NPR:

- High-boiling radiation-resistant low-activated lead coolant which does not react with water and air and hence affords low-pressure heat removal while excluding the possibility of fire, chemical and thermal explosions;
- High-density highly heat-conductive mononitride fuel operating at low temperatures (Tmax<1150 K, with Tmelt =3100 K), which limits the radiation swelling (~1 % per 1 % burnup) and fission gas release under the cladding;
- Core and lead reflector design, the composition and geometry of which affords fuel breeding, provides small and negative power, temperature and void effects of reactivity;
- Small reactivity inventory in the core (Δk/k<βeff) which rules out uncontrollable prompt criticality excursion in the event of inadvertent withdrawal of all control rods in any reactor condition.

Owing to this, it proved possible to abandon some engineered safety features which made this reactor (Fig.10) significantly cheaper than other fast reactors recently developed.

Nuclear Fusion as possible energy generation technology.

Today the demand of secure and sufficient supply of energy is mainly satisfied by fossil fuels (oil, coal and natural gas), which account for 80% of the total energy consumption. Secure and sustainable energy sources are required to maintain our standard of living.

Currently researchers from different countries are developing a range of environmentally acceptable, safe and sustainable energy technologies. Fusion is one of them [12].

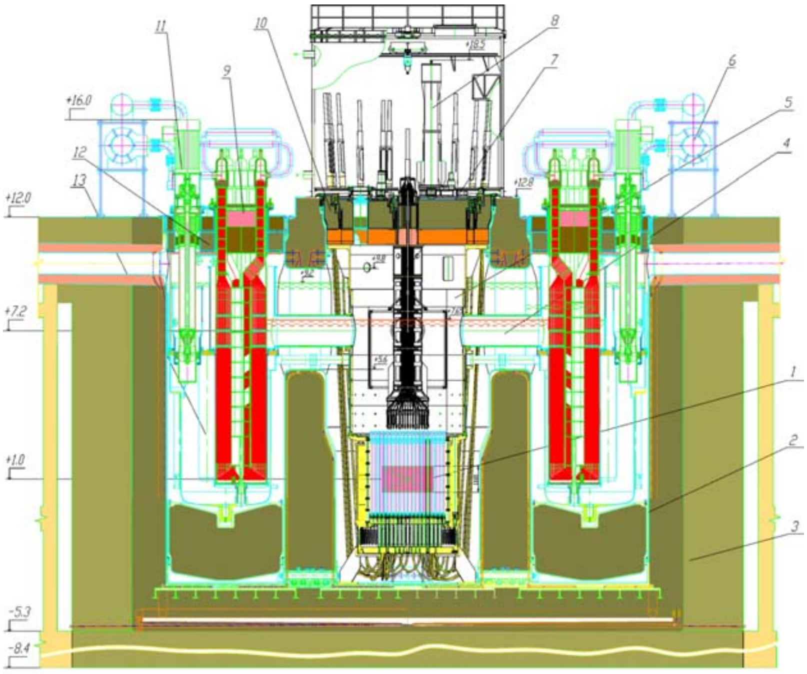

Fig. 10. BREST - 1200 MWt reactor as the basic innovative facility for the large-scale deployment of nuclear power
1 – core; 2 – liners; 3 – reactor shaft; 4 – lead pipeline; 5 – core basket; 6 – cooling system; 7 – instrumentation column; 8 – in-pile refuelling machine; 9 – steam generator; 10 – upper plate; 11 – main circulation pump; 12 – SG-MCP unit; 13 – filter

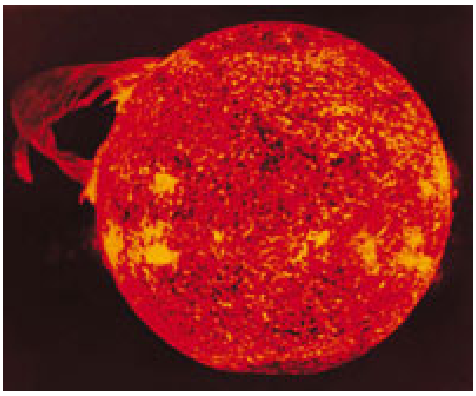

Fig. 11. The Sun is a massive fusion power station. It produces around 300 billion watts (3×10^{26}) of power, consuming 600 million tones of hydrogen fuel every second

For the long term, fusion will provide an option for a large scale energy source that has a low impact on the environment and is safe, with vast and widely distributed fuel reserves.

Fusion power stations will be particularly suited for base load energy generation to serve the needs of densely populated areas and industrial zones. They can also produce hydrogen for a “hydrogen economy”.

Fusion is the process which powers the sun and other stars. Nuclei of low mass atoms “fuse” together and release energy. In the core of the sun, the huge gravitational pressure allows this to happen at temperatures of around 10 million degrees Celsius (Fig. 11).

Gas raised to these temperatures becomes a “plasma”, where the electrons are completely separated from the atomic nuclei (ions). Plasma is the fourth state of matter with its own special properties. The study of these properties is the focus of plasma physics research. Although the plasma state is exotic on Earth, more than 99% of the universe is made up of plasma.

At the much lower pressures (10 billion times less than in the sun) that we can produce on earth, temperatures above 100 million degrees Celsius are required for fusion energy production rates of interest. To reach these temperatures powerful heating of the plasma is required and the thermal losses must be minimized by keeping the hot plasma away from the walls of its container.

This is achieved by placing the plasma in a toroidal “cage”, made by strong magnetic fields, which prevent the electrically charged plasma particles from escaping: it is the most advanced technology and forms the basis for the international fusion experiment ITER. It is also the world’s biggest energy research project which includes a global scientific and technical collaboration to produce an experimental facility that will demonstrate the potential of fusion power and test many of the components needed for a practical fusion power station. It is being built at Cadarache in the south of France and will be the world’s largest tokamak – a toroidal (or doughnut-shaped) device that uses complex magnetic fields to confine and compress the extremely hot fusion plasma (Fig. 12, Fig. 13).

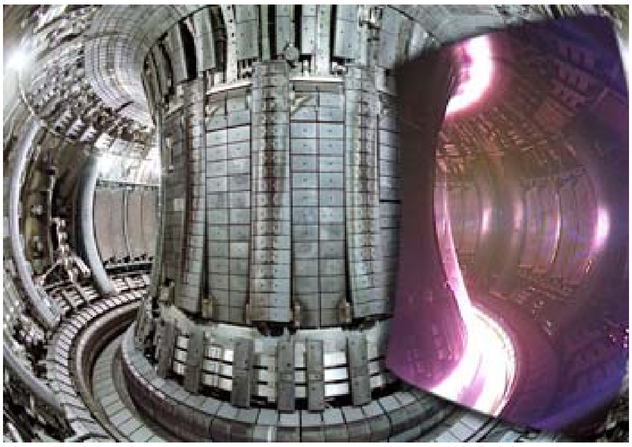

Fig. 12. Tore Supra (Cadarache-France), high-performance plasma discharge of record duration

Fig. 13. ITER electromechanical parts and divertor cassette

ITER is designed to study, for the first time, a “burning” plasma. it will be the first man-made fusion device to produce more energy than it consumes to heat the plasma. fusion reactions in ITER will generate around 500 MW of heat [13].

The fusion reactions between two isotopes of hydrogen – deuterium (D) and tritium (T) – provide the basis for the development of a first generation fusion reactor, as other fusion reactions require even higher temperatures. Deuterium is a naturally occurring, non-radioactive isotope and can be extracted from water (on average 35 g in every cubic meter of water). There is no tritium on Earth, but it will be produced from lithium (a light and abundant metal) inside the fusion reactor. Each fusion reaction produces an alpha particle (i.e. helium) and a high energy neutron.

$$\mathbf{D + T \Rightarrow {}^4He + n + 17{,}6\ MeV\ .} \qquad (1)$$

The neutrons escape from the plasma and are slowed down in a “blanket” surrounding the plasma. Within this blanket lithium is transformed into tritium, which is recycled back into the vacuum chamber as fuel, and the heat generated by the neutrons can be used to produce steam which drives turbines for electricity generation.

To supply a city with a population of about one million with electricity for one year, a fusion power plant would require one small truck-load of fuel.

A fusion reactor is like a gas burner: the fuel which is injected in the system is burnt. There is very little fuel in the reaction chamber (about 1 g of D-T in a volume of 1,000 m^3) at any moment and, if the fuel supply is interrupted, the fusion reactions last for only a few seconds. Any malfunction of the device would cause the plasma to cool and the reactions to stop.

The basic fusion fuels, deuterium and lithium, as well as the reaction product, helium, are non-radioactive. The radioactive intermediate fuel, tritium, decays reasonably quickly (it has a half-life of 12.6 years) and the decay produces an electron (beta radiation) of very low energy.

In air, this electron can travel only a few millimeters and cannot even penetrate a sheet of paper.

The energy generated by the fusion reactions will be used in the same way as today, e.g. for the generation of electricity, as heat for industrial use, or possibly for the production of hydrogen.

The fuel consumption of a fusion power station will be extremely low. A 1 GW (electric) fusion plant will need about 100 kg deuterium and 3 tons of natural lithium to operate for a whole year, generating about 7 billion kWh. A coal fired power plant – without carbon sequestration – requires about 1.5 million tons of fuel to generate the same energy.

Fusion reactors do not produce greenhouse gases and other pollutants which can harm the environment and/or cause climate change. The neutrons generated by the fusion reaction activate the materials around the plasma. A careful choice of the materials for these components will allow them to be released from regulatory control (and possibly recycled) about 100 years after the power plant stops operating. For these reasons, waste from fusion plants will not be a burden for future generations.

Proton – engine of the future energy generation method

Proton was discovered in the 20^{th} of XX century during the nuclear experiments with alpha particles. In the 70th by experiments of electron and gamma particles dispersion experiments the inner structure of proton was observed. At the same time up to now there are no information about the nature of proton, its properties and real inner structure (mass of the proton is 1836,1526675 - 39 e mass) [14].

Current research works shown that proton has a fractal structure, and novel model approaches decay of the proton is realized following the fractal algorithm. 10 stages of proton dissociation is following by appearance of simplest charged particles and energy generation [15].

$$\sum E_i = m_e c^2 \left[\frac{g_e}{2} \left(\sum_{i=2}^{11} 2^{12-i} \left(1 - \left(\sqrt[10]{D_e} \cdot \alpha^2\right)^i\right) + \left(2^{10} - 1\right)\left(1 - \left(\sqrt[10]{D_e} \cdot \alpha^2\right)^2\right) \right) \right] \quad (2)$$

E energy =107,7427553 MeV, and it is 11,5% of proton rest energy.
If the volume of outside energy influencing on proton is more then 107,74 MeV proton is becoming unstable (Fig. 14, Fig. 15)

$$\rightarrow \quad p^+ + \sum_{i=1}^{10} E_i \quad 1046 \text{ MeV} \quad (3)$$

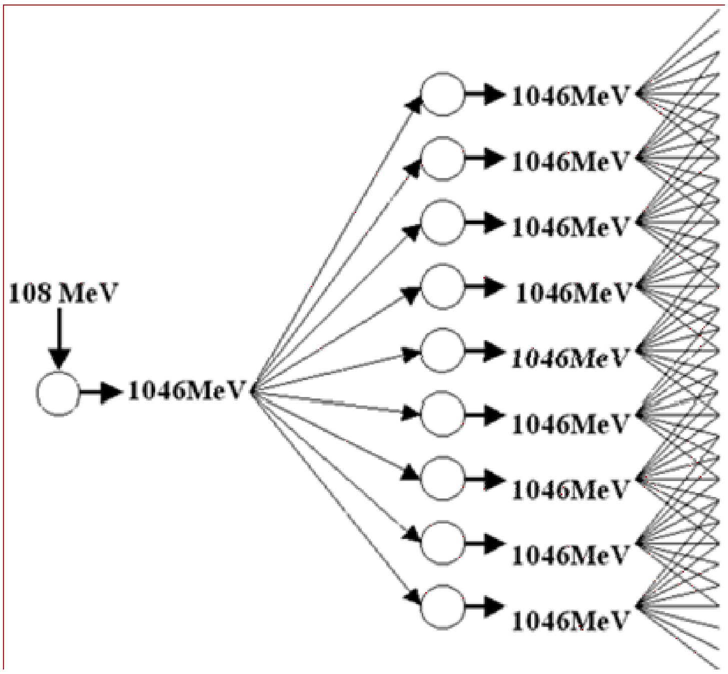

Fig. 14. Chain reaction of induced dissociation of Proton

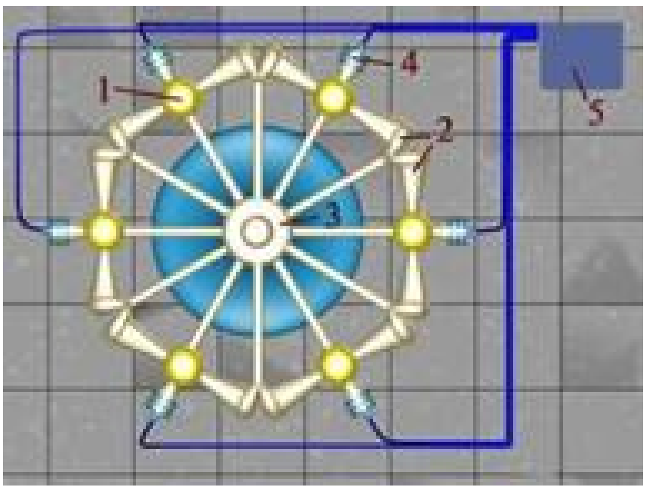

Fig. 15. Proton electricity generator general scheme:
1- reactor; 2-accelerator cones; 3-mixture, 4-electronic circuit; 5-control system

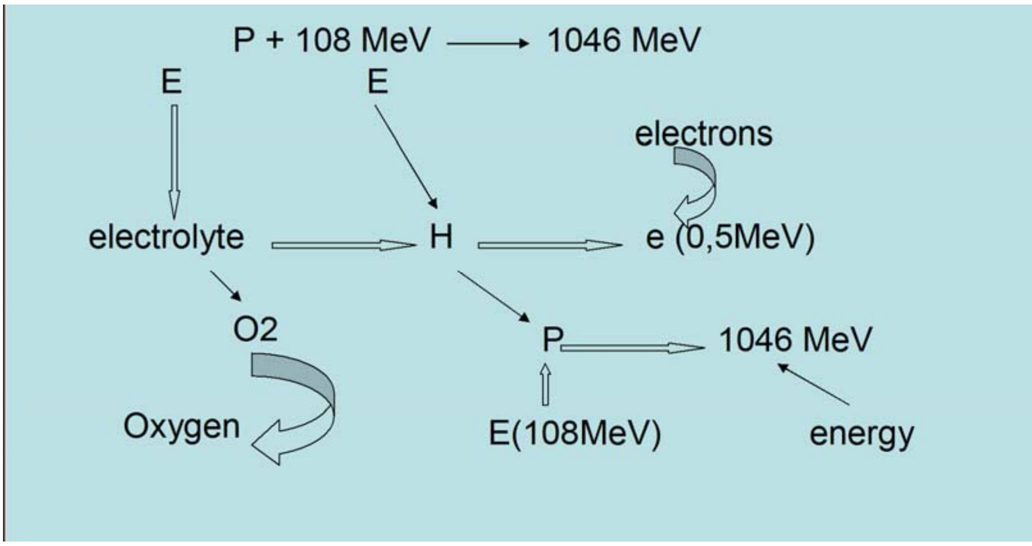

Fig.16. Proton born nuclear-chemical reaction

It was estimated that energy creating during induced dissociation of Proton is about 938 MeV.

For comparison energy generated during nuclear fusion is 17,6 MeV (Fig.16) [16].

Induced Proton dissociation should be very important nuclear effect, and its end products are not dangerous substances for biosphere.

Safety research for nuclear systems

Public acceptance is also an important issue for development of nuclear energy. Therefore research in the field of nuclear installation safety, protection of workers and population against radiation, management of all types of waste is one of the first tasks taking into consideration.

One of the main parts for solution of problem of technological safety of nuclear power installations is creation of relevant control system for nuclear reactors of different design [17].

The safety of nuclear reactors operating in prolonged life time conditions in many respects depends on the reliability of control and safety systems (CSS). In this regard, the role of the base of the nuclear reactors' CSS rods - neutron-absorbing elements (NAE) is being increased more and more, as well as their quality characteristics, which meet new, strict requirements [18].

The more hard operating needs are to be satisfied by rods of CSS for nuclear reactors on fast neutrons, the capacity of which directly depends on CSS [19].

For the practical applications to control systems in nuclear reactors far from all these elements fit this task. Among neutron absorbing elements the most preferable are based on the isotope B-10 absorbers in terms of efficiency in neutrons' intermediate and fast power spectra. They are distinguished by an optimal absorbing capability and heat-physical and physical-mechanical characteristics from the standpoint of their usability as NAE [20].

The importance of the utilization of boron - containing NAE as well of based on NAE rods of CSS for intermediate and fast neutron power reactors causes a great interest in the technologies of rods' fabrication and investigation of their properties.

Many monographs, articles and inventions are dedicated to nuclear power stations management and control facilities based on boron containing CSS. Alongside with that, it is necessary to be mentioned that at present many issues linked with the principles of technologies for their production as well as with the physics of relevant processes still are to be clarified.

The experience gained since 70s in the USSR, USA, France and other countries has shown that the development of highly effective CSS requires the realization of complex investigations in the fields of thermo physics and technology, as well as of radiation influence and reactor technology.

Of a highest significance is the definition of materials and mechanical structures for the utilization of different nuclear rectors, as well as the improvement of existing technologies for obtaining items with desired properties (structure, density of the thermal flows, thermo-physical properties).

At present, it is well known that the initial properties (phase composition, structure, heat-physical characteristics, etc.) of neutron-absorbing materials and items on their base have a governing influence on the effectiveness of fast reactors' CSS different rods and NAEs.

There was studied the corrosion resistance of items made from B_4C in sodium and its compatibility with stainless steel (NAEs housings' material). It was found out that the boron carbide and stainless steel components actively do not form chemical compounds with the pure sodium below temperature around 950^0C. At the same time, it was shown that the interaction takes place by the materials solving in a liquid metal with their consequent sedimentation upon the stainless steel surface and by diffusion through this surface. As a result, there is observed the boronizing and carbonization of NAEs housings' materials with all subsequent consequences. On the base of computation analysis it also must be mentioned that the corrosive resistance in sodium is strongly influenced by oxygen impurities in the liquid-metallic heat-carrier that rather negatively affects the operational stability of NAEs and CSS rods in total.

The behavior and durability of boron-containing elements in high parameters water (increased temperature and impurities concentration) also strongly depend on initial properties of reacting materials, temperatures and time parameters of their operation. In total, the corrosion resistance of high dense items made from the boron carbide enriched by the isotope B-10 up to 90% is very satisfactory in terms of their utilization in CCS rods' NAEs.

Structures of neutron-absorbing elements (NAEs) of CSS rods for reactors-breeders basically consist of metallic housings and compact items made from boron-contained materials enriched by the isotope B-10 (Fig.17).

NAEs the number of which in most of rods is 7 are gathered in a cluster inside the housing's pipe and fixed in upper and lower parts of the CSS rod. In most of cases AEs are hermetically sealed and their structurally consist of the proper absorbing part and the gas collector where the accumulation of helium takes place. The formation of helium in the absorbing material during its exploitation in the neutron irradiation field is caused by the n, α nuclear reaction.

At present, the role of NAEs basically is performed by made from enriched B_4C compacted items of two configurations: cylindrical and annular. NAEs structures and sizes depend on configuration and parameters of the reactor-breeder's active zone. Main problems in terms of NAEs working capacity occur basically because of the temperature field's nonuniformity and also due to gas swelling of their components [21].

Because of high temperature and mechanical loading the NAEs are being regularly surveyed during their exploitation as well as thoroughly studied in special so called "hot chambers" after "campaign" is over. Main damages typical of NAEs during their exploitation are form-changing and NAEs housing's deformation caused by the radial loading. It is worth mentioning that during a long exploitation and in presence of curved neutron fields very often the disturbance of NAEs housings' hermiticity takes place. It causes the gas accumulation in rod's hollows and thus the sharp impairment of its working capacity's parameters. In this regard, frequently are used the so called untaught NAEs while in the rods structure there is provided a possibility removing gases formed as a result of nuclear reactions.

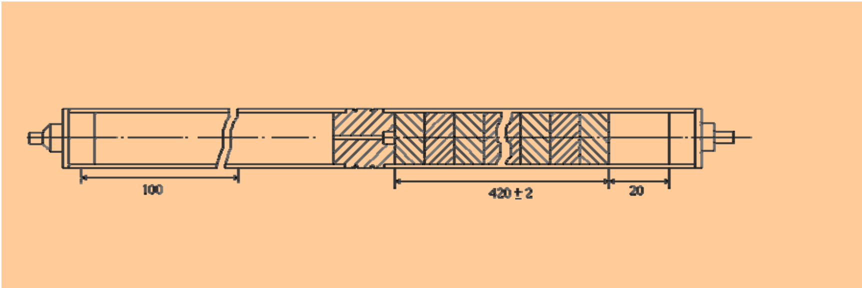

Fig.17. The Simple Model of Neutron Absorbing Element for Fast Nuclear Reactor Regulating Rod

One of positive factors of the utilization of neutron-absorbing items made from the boron carbide is their gas swelling's linearity that allows to maintain the structural stability of AE, and hence - of the rod, even in cases of their fast burn-out and heating to high temperature when the emergency stoppage of the nuclear reactor i.e. the rapid insertion of rods into the active zone of the fast reactor take place.

In fast reactors there are used three types of controlling rods. They are rods of fine control, coarse control and emergency rods. Functions of each of them are either the control of nuclear reactivity or stoppage of reactor's operation. Controlling rods serve for reactivity's compensation during the run, temperature increase, burning out and external effects. In particular, from the standpoint of fine adjustment controlling rods' function - reactor's control, the most important parameter of these rods is the control's rapidity. Emergency rods serve specially for emergency stoppage of the nuclear reactor as rapidly as possible.

Rods for compensating the reactivity of the reactor-breeder usually have a structure consisting of seven absorbing elements (NAE) gathered in a cluster inside the housing tube (Fig.18). In the lower part of the rod NAEs are rigidly fixed (usually welded), while in the upper part they move freely in axed direction. NAEs are hermetic and structurally consist of neutron-absorbing part and gas collector. Basically, they are made from cylindrical modules B_4C enriched by the isotope B-10. During exploitation such a compensation rod (CR) is located in the central cell of the active zone and as the uranium-plutonium fuel is being burnt out the CR moves upward.

Among the CCS rods intended for the emergency stoppage of the reactor-breeder the most optimal is the structure of the emergency guard rod (EG) worked out for the energetic nuclear reactor "BN-600" (Fig.19). It consists of the head, upper extension section, two neutron-absorbing sections and lower extension section.

NAEs of such a rod usually are made from B_4C enriched by the isotope B-10 up to 80%. The rod is not hermetic, in its upper end component are two inter-perpendicular apertures. The internal volume, through the groove seal between the upper end component and the jacket as well as through special apertures is linked with the heat-carrier. There takes place the initial filling of gaps by the liquid-metallic heat-carrier - sodium as well as the exit of a heat generated during the exploitation.

Last years, according to active zones' parameters of reactors-breeders there are used CCS rods of other structures.

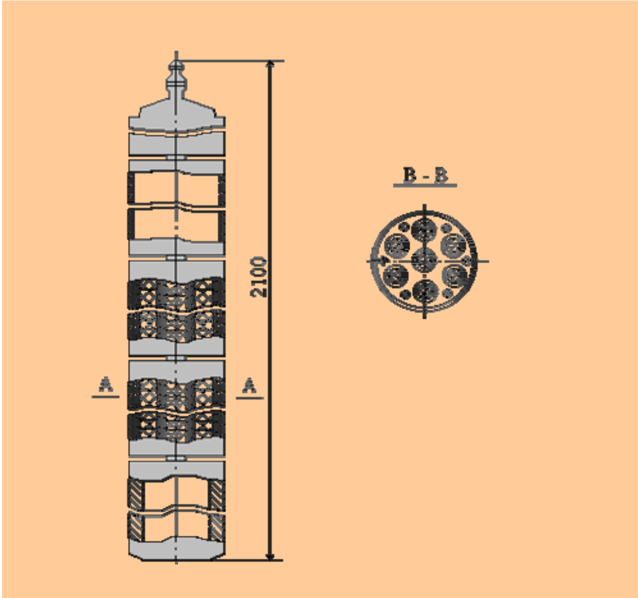

Fig.18. Reactivity Compensation Rod Design

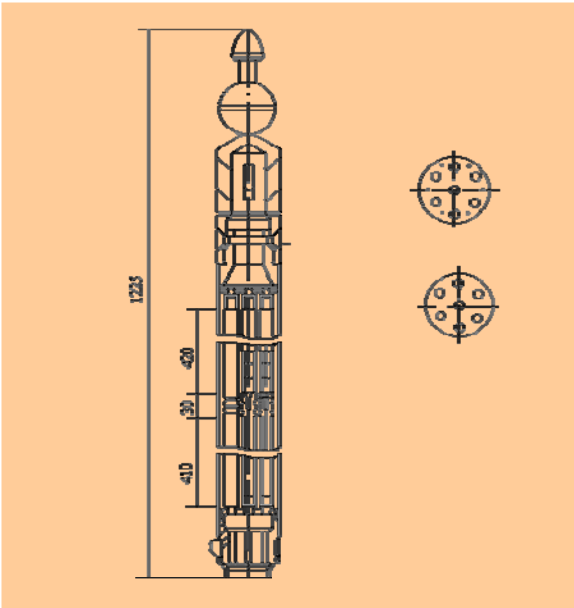

Fig. 19. Emergency Protection Rod Design

The temperature compensation rod (TC) of nuclear reactor's active zone (Fig.20) basically is made from NAEs where the composition of europium oxide and metallic molybdenum (Eu_2O_3 + Mo) serves as a neutron-absorbing material. In this rod, inside the absorbing working section there are located 48 absorbing elements. As are encapsulated by end components and welding. They can be of an assorted type (consisting of modules or cylinders) and of a filled type. Rods with filled NAEs are approximately 2 times cheaper due to the high capacity and absence of any waste of Eu_2O_3 during the fabrication of their tablets the hot compacting method.

The rods-traps are among the most prospective reactors-breeders' CCS rods. In these rods (their structure is shown in the Fig. 21) the role of neutron-absorbing element was performed by tablets made from europium oxide (Eu_2O_3) or ring items from boron carbide (B_4C) enriched by boron-10 up to 92%.

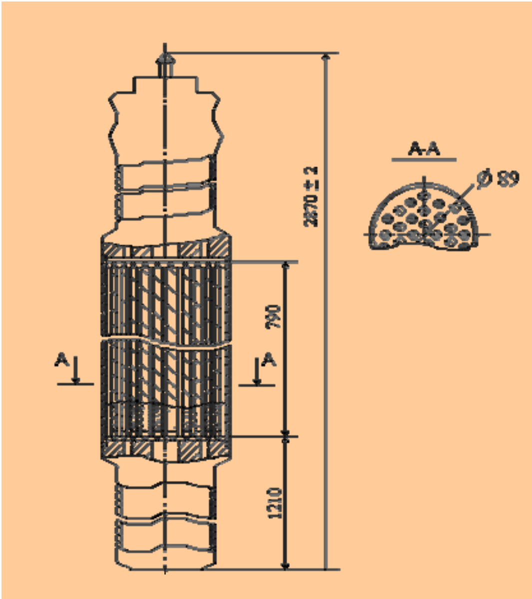

Fig. 20. Temperature Compensation Rod Design

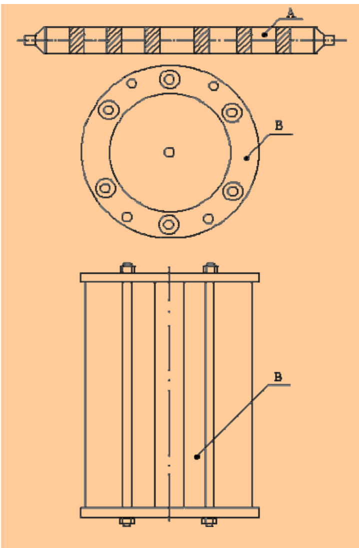

Fig. 21. The Scheme of the Neutron Absorbing Element-A and Trap-Tipe Regulating Rod

Experiments carried out for determining comparative effectiveness of rods-traps on the critical assemblages with plutonium fuel have shown that such CCS' rods structures provide the increase of the neutrons absorption effectiveness (working capacity) by up to 10-20% according to characteristics of neutron field and other parameters of the nuclear reactor's active zone.

In order to increase the effectiveness of CCS rods operating in the high energy neutrons field as well as to improve their reliability some interesting structures were worked out.

For ameliorating NAEs cooling conditions there is developed the rod in which absorbing elements have a form of a disk with central aperture and are bordered from top and bottom by conic surfaces (Fig 22). The angle of a slope of the absorbing elements' lower surface is larger than that of the upper one and between them capillary gaps for the heat-carrier moving.

While the rod operates within the nuclear reactor's active zone there actively circulates in the internal space of rod the liquid-metallic heat-carrier the more cold part of which flows downward and the warmer one - upward. Alongside with that the heat-carrier moves in broadside direction from periphery to centre. Finally, it provides the substantial improvement of the heat transfer from neutron-absorbing NAEs [22].

For ameliorating the evenness of the burning-out process of a neutron-absorbing material there is developed the CCS rod's structure including the container for powder-absorber with permeable walls (Fig.23). While the rod operates within the reactor-breeder's active zone the engendered by the nuclear reaction process of heat liberation continuously takes place in the bulk of the powder-absorber. At the same time, there appear temperature conditions sufficient for organizing the liquid-metallic heat-carrier's boiling process. The liquid-metallic heat-carrier of relatively low temperature penetrates into container trough external walls moving trough and cooling the absorbing material. During this process it gets warmed itself, turns into the gas-liquid mixture and enters the rod's central channel. The container's volume and powder-absorber's amount is selected with regard for providing powder's continuous, slow agitation having the mean circulation directivity, the migration results in powder's displacement upward in the central zone. In such agitation conditions the whole neutron-absorbing material will be burnt-out evenly. Such structure of the controlling rod is attractive because of the fact that the absorber's agitation process, hence its even burn-out, runs without using any drive mechanisms, external motor means and engines. All this has a positive effect on the effectiveness and reliability of the nuclear reactor's whole controlling and security system [23].

Last years there is intensively going on an activity focused on creating new highly effective and reliable CCS rods for fast energetic nuclear reactors. Structural particularities of modern rods are determined by new optimizing neutron-absorbing elements as well as by the necessity of providing optimal heat- and thermo-mechanical conditions for their exploitation.

Conclusions

At present, in the electricity generation sector: fossil fuels supply around 65% of world electricity demand; renewable sources just over 18%; and nuclear generation provides the remaining 17%. Together these sources currently generate nearly 15 500 TeraWatt-hours (TWh). However, based on the lowest estimates of future electricity demand, this output must increase to nearly 22 000 TWh over the next 20 years. Even with growth rates of 10% in capacity, wind and solar power sources are unlikely to meet more than 1% of world energy needs by 2020. Among countries with nuclear power generators, in May 2004, total electricity consumption from nuclear energy sources was generated by 441 nuclear power plants (NPPs) ranging from over 80% in Lithuania to around 1% in China. New capacity under construction in the Far East suggests that nuclear energy supply in the region will be at least tripled. Further, here in Europe, Although the public is not yet convinced, experts believe that geological disposal is technologically feasible, environmentally responsible and ultimately safe. Finland, Sweden and the United States lead in implementing this form of repository technology, and several other countries are actively investigating geological disposal as a viable option, often establishing underground research facilities for this purpose.

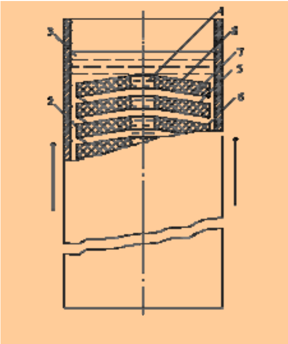

Fig. 22. The Scheme of Advance Regulating Rod with Better Cooling Conditions

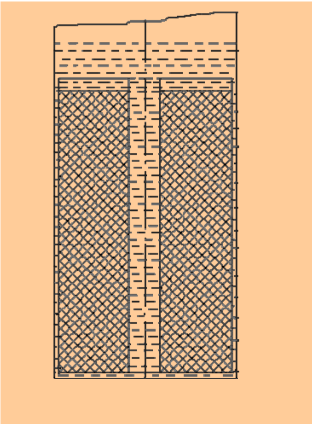

Fig. 23. The Scheme of the Regulating Rod with the good burn up properties

The position of nuclear power within the overall global mix of sustainable energy options must be clarified in relation to future commercial efficiency and developmental needs.

A principal milestone which has identified recently is the development of a “new generation of nuclear facilities” that centre on innovative reactor design and fuel cycle technologies. In addition to being economically competitive, these new technologies must be inherently safe during operation, produce a minimum of waste and also negate nuclear-proliferation issues. Only through meeting these conditions can public acceptance of nuclear energy be gained.

These new generation technologies will have to be flexible in order to satisfy the energy needs of developing countries, and also adaptable to a broad range of environmental and industrial requirements. In this way, the IAEA foresees the need for small and medium sized reactors, which can produce not only grid based electricity as necessary, but also provide power locally for local needs, such as seawater desalination and domestic heating.

Another major goal is to develop definitive strategies for the disposal of spent fuel and high-level radioactive waste, and in addition to disposal technologies, efforts continue to minimise the radiative nature of nuclear waste by developing methods that accelerate radioactive decay over time, or convert nuclear waste directly through transmutation techniques.

It is now recognised globally that there is a progressive loss of nuclear expertise and that, for the industry to be sustained or developed, this trend must be halted and reversed. This disappearing expertise is represented by highly qualified and trained nuclear engineers and scientists whose knowledge is central to the operation and maintenance of current nuclear plants, and also to decommissioning and waste management.

One of the major obstacles to the future of nuclear power as a readily accepted source of energy is how it is perceived by society at large. In addition to their obvious benefits, all modes of power generation have disadvantages.

Only through understanding all aspects of each technology (including security of supply aspects) can a balanced assessment be made of any given nuclear energy source.

Remarkable performance of nuclear power plants, including nuclear technologies in both the medium and long term is the basis for the future rapid development of nuclear energy worldwide.

Most important tasks are development the nuclear technologies provides the safety and security of nuclear energy generated systems, and among the novel materials and compounds, novel microsystems based nuclear instruments and devices for nuclear reactors control networks.

For instant, investigations focused on the development of CSS rods for different types of nuclear reactors carried out for last two decades in countries possessing nuclear technologies showed the expediency and possibility of building their various structures providing effective and reliable operation. At the same time, it is sufficiently neatly fixed that the most appropriate absorbing elements are isotope- enriched boron compounds as well as compositions of rare-earth metals.

The performed technological, physical-mechanical and radiation tests clearly indicate the prospects of using B-10 containing NAEs during the creation of highly effective CSS rods on their base.

In this respect, particular attention is to be paid to the development of new and upgrading of existing computing models as well as effective technologies for producing the novel generation of items characterized by all physical and strength properties necessary for obtaining desirable operational parameters of novel nuclear materials and tools.

R E F E R E N C E S

1. Kervalishvili P. Utiamyshev I., Some new human friendly energy production technologies.
2. International Scientific Journal for Alternative Energy and Ecology N 1 (33) 2006. pp. 21-29.
3. Brundtland Report: Our Common Future, the World Commission on Environment and Development, Oxford University Press, 1987.
4. European Council 8-9 March 2007, Brussels, Presidency Conclusions, 7224/07, Annex I, European Council Action Plan (2007-2009), Energy Policy for Europe (EPE) 10 January 2007.
5. Nuclear Illustrative Programme (PINC), COM(2006) 844, published in January 2007, and Annexes 1 and 2, SEC(2006) 1717 and SEC(2006) 1718.
6. The WEC Survey of Energy Resources (1995) estimates that for fast reactors, proven uranium resources allow for more than 3 000 years of energy production; http://www.worldenergy.org/wec-geis/edc/scenario.asp

7. International Conference on Nonelectric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and Other Applications, 16-19 April 2007, Oarai, Japan.
8. World Nuclear Association – http://www.world-nuclear.org/info/ reactors.html, updated on 31 May 2000.
9. Generation IV International Forum, 2008 – www.gen-4.org.
10. Gabaraev B.A., Cherepnin Yu.S., Innovative Designs of Nuclear Reactors. NATO Advanced Research Workshop "Nuclear Safety and Energy Security", Yerevan, Armenia, 26-29 May 2009.
11. Feretic D., Čavlina N., Grgić D., PotentiaI advantages and disadvantages of sequentiaIly building smaIl nuclear units instead of a large nuclear plant. Kerntechnik 73, (2008), pp.249-253.
12. Kervalishvili P.J., Prospective energy generation technologies. Scientific - Economic Magazin, 2015, Noema, Bergamo, Italy. 2009, pp. 27-38.
13. Arnoux Robert, Jacquinot Jean. Iter: le chemin des etoiles? Edisud 2007.
14. Sakharov A.D. Violation of invariance; C-symmetry and barion asymmetry. Letter to JETF, v. 5, 1967, pp. 33-35.
15. Kosinov N.V. Fractal rules in physics of microworld. Physics of consciousness and life, cosmology and astrophysics, no 4, 2003, pp. 45-56.
16. Jakob M., Landshoff. Inner structure of proton. UFN, v. 133, No 3, 1981, pp. 14-42.
17. International Atomic Energy Agency (IAEA). A Newsletter of the Division of Nuclear Power. Vol. 6, No. 2, June 2009. http://www.iaea.org/NuclearPower/.
18. Kervalishvili, P. J. Investigations Focused on Development of Control and Safety Rods for Fast Nuclear Reactors-Breeders. Proceedings of the XVI PanHellenic Conference on Physics, September 17-20 2000, Naphleon, Greece, Ed. Praktika, 2001, Athens, Greece.
19. Kokaya M.V., Kervalishvili P.J., Kalandadze G.I., Cadmium Based Neutron Absorbing Materials. J. Atomhaya Energya, Vol.63, 1987, pp.273-275.
20. Kochetkov L.A., Kazanskey Y.A., Matveev V.I., Investigation on effectivity of Rods-Traps for Fast Neutrons Nuclear Reactors". Report of the Institute for Physics and Energy, Obninsk, N141, 1985, 196p.
21. Bakhtadze A.B., Bairamashvili I.A., Kervalishvili P.J., Structural Defects Influence on Boron Carbide Thermoconductivity. Academy of Sciences of USSR, J. Neorganicheskie Matereialy, Vol.25, N 10, 1989, pp.1652-1665.
22. Bakhtadze A.B., Shekriladze I.G., Kervalishvili P.J., Regulating Rod for Nuclear Reactor, USSR Invention, N 830924, 1980.
23. Bakhtadze A.B., Kervalishvili P.J., Shekriladze I.G., Nuclear Reactor Control Rod, USSR Invention, N 936731, 1980.
24. Kervalishvili P., Some Neutron Absorbing Elements and Devices for Fast Nuclear Reactors Regulation Systems. Nuclear Power and Energy Security, NATO Science Series – B Physics and Biophysics, v. 147, Springer Science + Business Media, 2010, pp.147-155.

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